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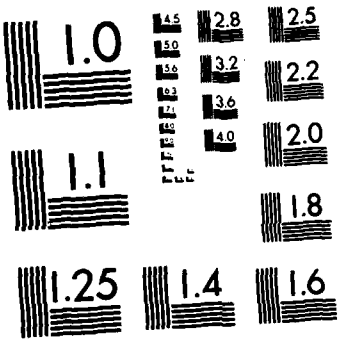

REPORT SD-TR-83-05

High-Performance DF-CO_2 Chain-Reaction Laser

S. T. AMIMOTO, J. S. WHITTIER, G. HARPER, and R. HOFLAND, Jr.
Aerophysics Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, Calif. 90245

J. M. WALTERS, Jr. and T. A. BARR, Jr.
U. S. Army Missile Command
Redstone Arsenal, Ala. 35898

and

R. L. KERBER and W. K. JAUL
Michigan State University
East Lansing, Mich. 48824

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Prepared for

SPACE DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, Calif. 90009

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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Steven G. Webb, 1st Lt, USAF
Project Officer

David T. Newell, Lt Col, USAF
Acting Dir, Space Systems Technology

FOR THE COMMANDER

Norman W. Lee, Jr., Col, USAF
Commander, Det 1, AFSTC

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Performance of a pulsed DF-CO_2 transfer laser was investigated for the case of transverse initiation by a magnetically confined electron beam. Laser output is presented as a function of e-beam charge fluence, O_2 concentration, F_2 concentration, diluent gas, and total mixture pressure. The experimental data are compared with the predictions of a comprehensive rotational-nonequilibrium DF-CO_2 laser model. Experimental results include a 41 J/ℓ CO_2 output at 800 Torr cavity pressure and the

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potential for system electrical efficiency in excess of 100% when the dimension along the axis of e-beam propagation is made comparable to the range of the electron beam. The DF-CO_2 laser performance is found to be comparable to that of a DF chain laser using mixtures of comparable chemical energy content.

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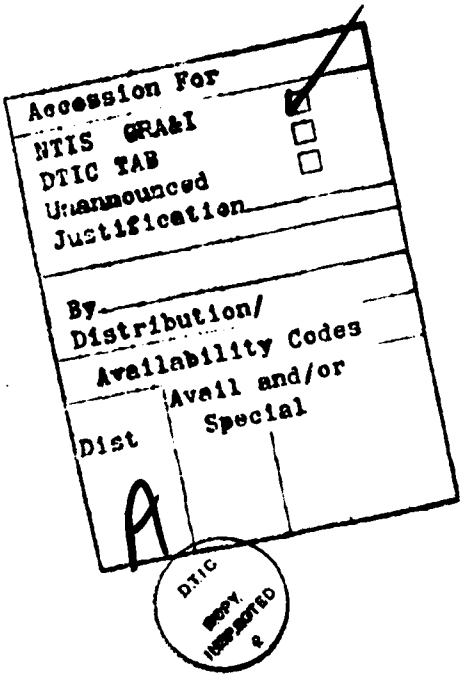

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FIGURES

I. INTRODUCTION

The problem of photolysis initiation of pulsed DF-CO_2 transfer lasers has been studied by a number of investigators.[1-14] Interest in pumping a CO_2 laser by use of the D_2-F_2 chain reaction is motivated both by the simplicity of photolytic initiation compared with e-beam-controlled excitation and by the possibility of high energy-density output. In a recent demonstration, Basov et al.[1] reported output energies of 150 J/ℓ and chemical efficiencies of 7% from a DF-CO_2 amplifier system operating with nondilute mixtures. Chemical efficiencies as high as 15% have been measured for a transfer laser, but only for the case of highly buffered mixtures that yielded low energy-density outputs.[2]

Theoretical models of the DF-CO_2 system have evolved that address effects of initiation level and gas composition on laser performance,[3-6] short pulse generation,[7] laser performance at 16 μm,[8] and amplification by photon branching.[9] Performance of an electron-beam-initiated DF-CO_2 laser has been briefly examined by Bashkin et al.;[15] e-beam initiation has received little attention in comparison with the photolytically initiated case. The present investigation extends the work of Ref. 15 to longer e-beam pulse lengths and lower current densities, and includes the effect of a confining transverse magnetic field. The apparatus of this study has been previously employed to investigate the performance of HF(DF) chain lasers.[16]

The extension to the DF(HF)-CO_2 transfer-laser case reported herein was intended to establish scale-size and repetition-frequency limitations at CO_2 wavelengths and, hence, to establish scaling limitations for multicolor laser operation in general. Simultaneous demonstration of high energy-density output and the potential for high electrical efficiency was an additional objective of the present investigation.

II. EXPERIMENTAL TECHNIQUE

The DF(HF)-CO_2 transfer laser was initiated by means of a pulsed electron-accelerator system that was modified for generation of long-duration e-beam pulses and confinement by strong magnetic fields.[16] The electron gun was driven by a pulse-forming network comprised of a four-stage Marx generator, a low-impedance coaxial water line that was operated as a peaking capacitor, and a high-voltage output switch. A thermally-conditioned carbon-felt emitter was found to produce uniform electron emission in the presence of a strong confining magnetic field. On the vacuum side of the electron window was located one element of a Helmholtz coil through which an e-beam of 5 × 100 cm cross section was transmitted. A second coil element was positioned at the rear of the laser chamber so as to produce a nearly uniform confining B field within the volume of the active laser medium. Magnetic fields of up to 1.3 kG could be produced with this Helmholtz coil arrangement. At the exit of the anode window, a uniform (± 10%) beam of 20 A/cm^2 current density and 175 keV energy was transmitted across the laser cavity. A low-inductance crowbar switch located at the output of the Marx generator was used to obtain continuously variable e-beam pulse lengths in the range 0.2 to 1.2 μs. Diagnostic measurements of Marx current and voltage, total diode current, e-beam current density, and diode accelerating voltage were obtained during each laser test.

Energy was extracted from the active gain medium by means of a confocal unstable resonator of magnification 2.8. Resonator elements consisted of highly polished uncoated copper mirrors of high optical figure. The nominal Fresnel number of the unstable resonator was 160. Laser windows were 1.25-cm-thick ZnSe substrates that were antireflection coated at 10.6 μm. The clear apertures of the cavity elements limited the optical extraction volume to 2 ℓ, as verified by near-field burn patterns. Commercial-grade gases were metered and mixed in an aluminum mixer block prior to their introduction into the laser cavity. Laser pulse energy was measured by means of ballistic thermopiles having 4-cm and 9-cm entrance apertures. The bulk of the laser

pulse energy was directed into the 9-cm calorimeter on every test. A redundant measurement of laser output was provided by a NaCl beam splitter and a focusing lens that directed about 4% of the pulse energy into the 4-cm calorimeter. Emission time history of the laser was monitored with both Au:Ge and photon-drag detectors.

III. RESULTS AND DISCUSSION

Data obtained during a typical laser experiment are presented in Fig. 1. A mixture consisting of 11% F_2: 11% D_2: 51% CO_2: 0.3% O_2: 26.7% He by molar volume was irradiated at an initial cavity pressure of 400 Torr. The measured CO_2 pulse energy of 50 J corresponds to an output energy density of 25 J/ℓ (48 J/ℓ atm) . The Faraday cup record of Fig. 1 shows that the peak e-beam current density for this case was 22 A/cm^2 and the FWHM pulse duration was 455 ns. A capacitance divider at the end of the pulse-forming line showed the peak cathode voltage during the e-beam pulse to be [illegible] kV.

Time history of the laser irradiance is illustrated by two dual-beam oscillograms in the upper half of Fig. 1; both fast (50 [illegible]v) and slow (500 ns/div) sweepspeed data were obtained for this test. The upper oscillogram trace is the output of the photon-drag detector, while the lower trace is the gold-doped germanium detector output. Poor low-frequency response of the photon-drag detector is clearly evident when its waveform is compared with that of the Au:Ge detector. The overall laser FWHM pulsewidth is observed to be 1.4 μs. Each detector shows a 50-ns-wide gain spike and the presence of mode-beating effects; both features are characteristic of CO_2 lasers[17] and are absent during emission from a pulsed HF/DF chain laser.[16] The observed mode oscillation period of 18 ns agrees closely with the time for a cavity round-trip (16.9 ns). Further confirmation of CO_2 lasing was obtained by inserting narrow-bandpass filters (3.5 to 4.5 μm or 9 to 11 μm) into the laser beam.

Dependence of DF(HF)-CO_2 laser performance on several parameters has been studied. Sensitivity of output energy to O_2 concentration in the laser mixture was studied first (Fig. 2) because of the strong oxygen effect observed in our earlier HF/DF chain-laser work.[16] The best performance for the DF-CO_2 transfer laser was found to occur at an oxygen concentration of 0.3%. Lower O_2 concentrations were found to give spontaneous (premature) ignition of reactants in our low-velocity flow-handling apparatus. The degradation of laser output with the inclusion of a chain-terminating species, such as O_2, is anticipated for the present laser since chain propagation is the basis upon

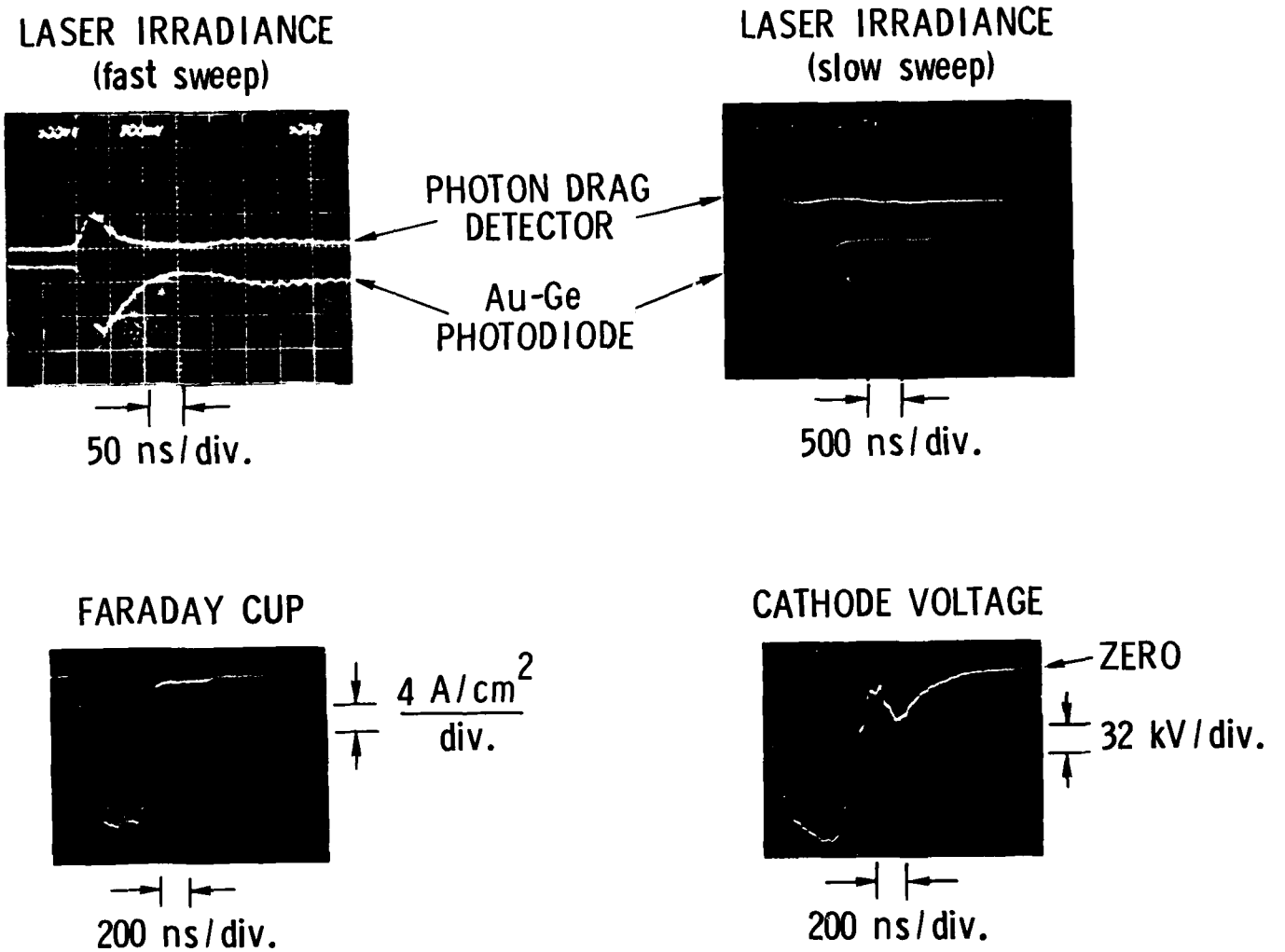

Fig. 1. Oscillograms of DF-CO_2 Laser Output Irradiance, E-Beam Current Density, and E-Gun Cathode Voltage. Laser pulse energy and incident e-beam charge fluence were 50 J (48 J/ℓ atm) and 9.9 μCb/cm^2, respectively. Other conditions were a 1.3-kG confining B field and a 400-Torr mixture consisting of 11 F_2: 11 D_2: 51 CO_2: 0.3 O_2: 26.7 He by molar volume.

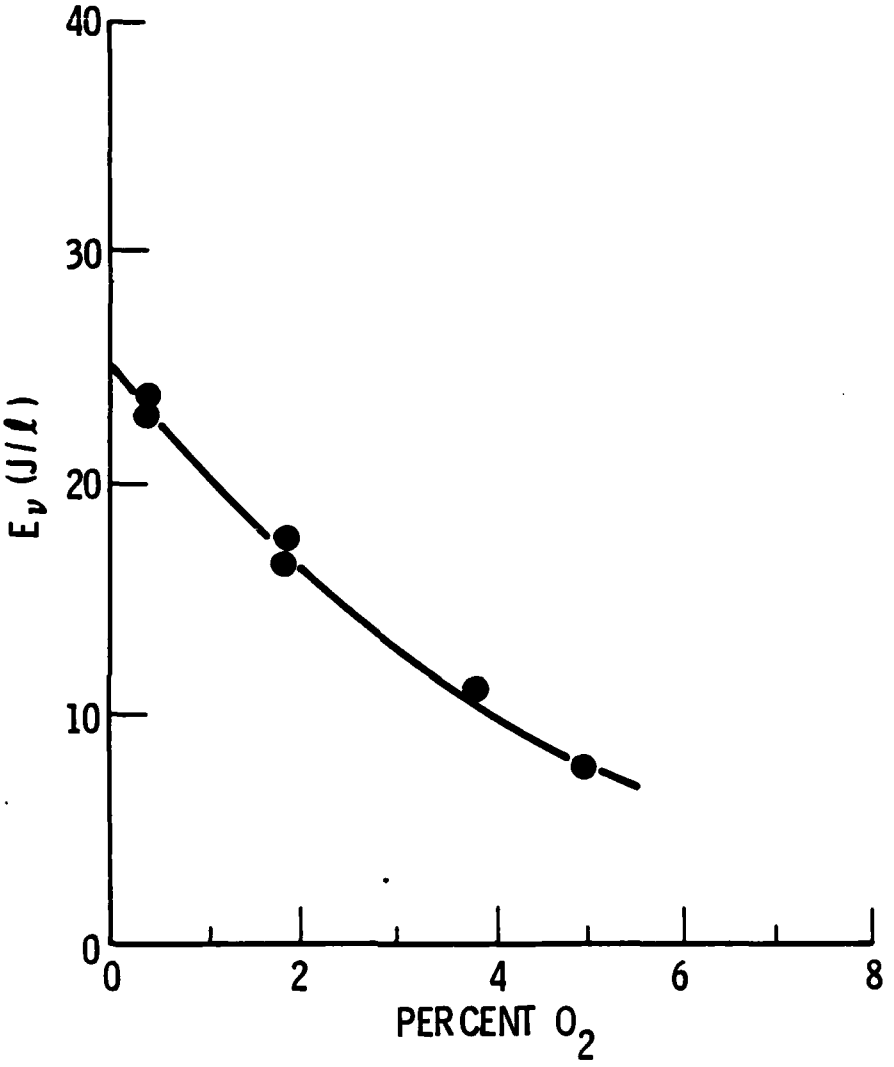

Fig. 2. Effect of O_2 on DF-CO_2 Laser Performance. Specific energy output from 11 F_2: 11 D_2: 51 CO_2: xO_2: (27-x) He mixtures at 400 Torr pressure is plotted as a function of oxygen concentration. E-beam charge fluence is 5-10 μCb/cm^2.

which the present laser operates. An approximate expression for the fractional laser-energy degradation resulting from the presence of O_2 can be written as[18]

$$E_{O_2}/E_{O_2=0} = (1 + \tau_\upsilon \, n_{O_2} \, \Sigma_i \, k_i \, n_i)^{-1} \qquad (1)$$

where τ_υ is the laser pulse duration, n_i is the initial number density of species i, and k_i is the rate coefficient for the chain-terminating reaction

$$H + O_2 + M_i = HO_2 + M_i \qquad (2)$$

Eq. (1) has been fit to the data of Fig. 2 to obtain an estimate for the unknown rate coefficient for Eq. (2) with CO_2 as a collision partner. If one assumes[19] $k_{D_2} = 1.4 \times 10^{-32}$ exp [500/T (°K)] cm^6/s and $k_{F_2} = k_{He} = 4.1 \times 10^{-33}$ exp [500/T (°K)] cm^6/s, then the data of Fig. 2 imply that $k_{CO_2} = 4.7 \times 10^{-32}$ exp [500/T (°K)] cm^6/s.

The effect of initiation strength $(F/F_2)_i$ on CO_2 output was studied by holding the e-beam current density constant and varying the e-beam pulse duration and, hence, the incident charge fluence. Laser output energy density is plotted as a function of e-beam charge fluence in Fig. 3. The performance of both DF-CO_2 and HF-CO_2 transfer lasers was examined. For the HF-CO_2 laser case, specific energy is seen to be extremely low and nearly independent of charge fluence. The poor performance of this system as a transfer laser is consistent with the large mismatch in energy levels between HF(v) and CO_2 (00°1). For the DF-CO_2 transfer laser case, a five-fold increase in charge fluence produced a 50% increase in output energy density (from 17 to 25 J/ℓ), i.e., $(J/\ell)_{DF\text{-}CO_2} \sim (\mu Cb/cm^2)^{1/4}$. A similar output-energy dependence on initiation level can be inferred from earlier theoretical studies of the DF-CO_2 transfer-laser system.[3,5,6] The DF-CO_2 laser dependence on charge fluence was found to be extremely weak compared to that of the D_2-F_2 laser; for the latter case, we have observed[16,20] $(J/\ell)_{DF} \sim (\mu Cb/cm^2)^{1/2}$.

The dependence of specific output energy on reagent concentration, F_2 and D_2, is illustrated in Fig. 4 at a cavity pressure of 400 Torr. In this para-

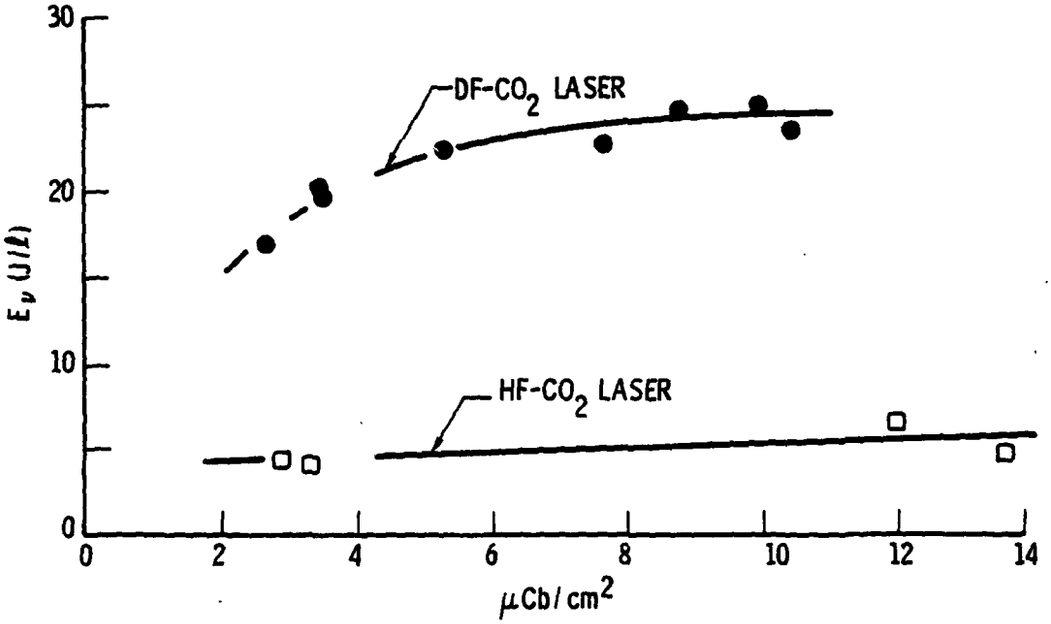

Fig. 3. Charge Fluence Scaling for DF-CO_2 and HF-CO_2 Chain-Reaction Transfer Lasers. Specific energy output from 11 $D_2(H_2)$: 11 F_2: 51 CO_2: 26.7 He: 0.3 O_2 mixtures at 400 Torr initial pressure as a function of e-beam charge fluence.

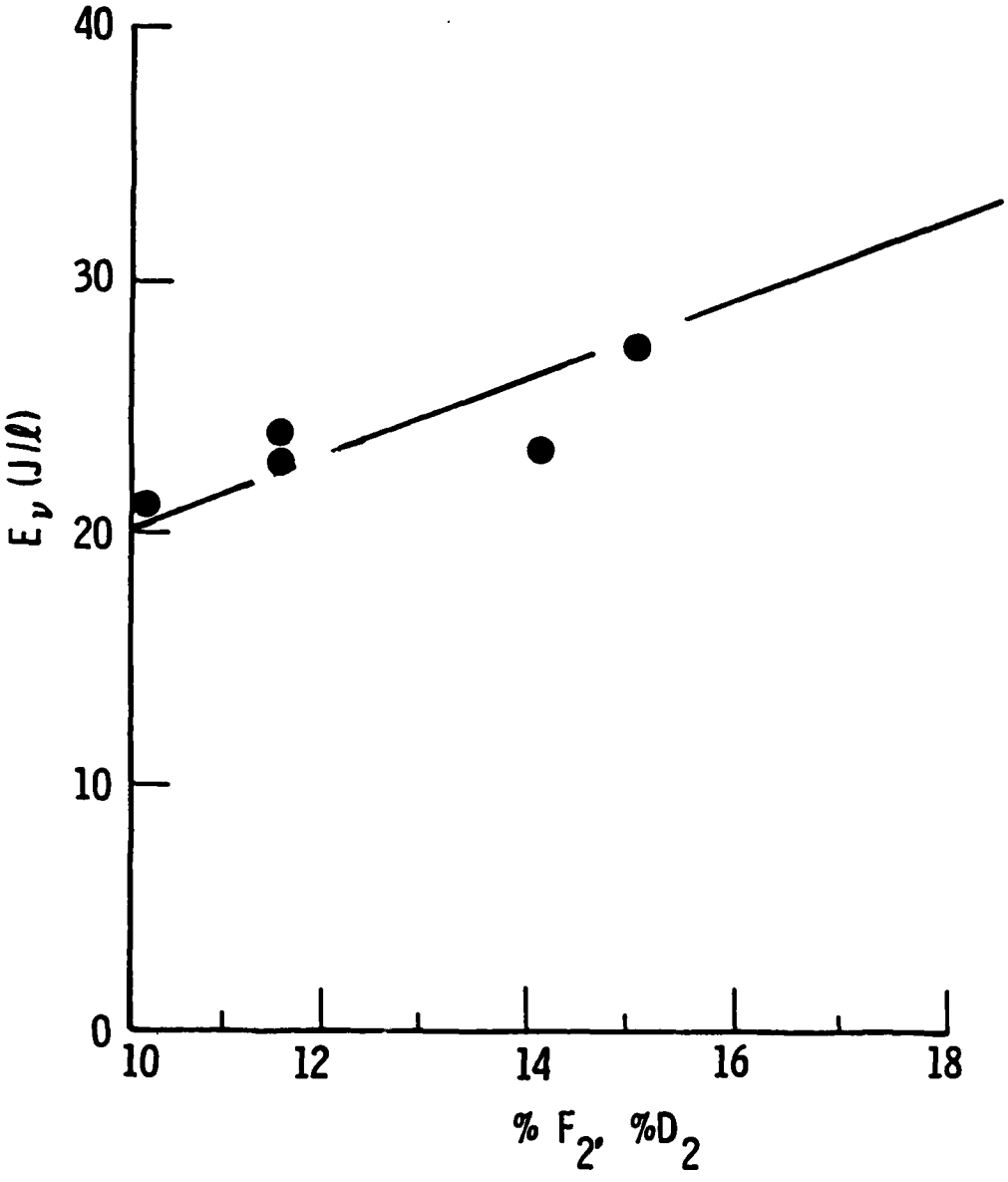

Fig. 4. Effect of Mixture Chemical Energy Content on DF–CO_2 Laser Performance. Specific energy output from xF_2: xD_2: 0.3 O_2: 26.7 He: (73–2x) CO_2 mixtures at 400 Torr initial pressure as a function of F_2 (D_2) concentration. E-beam charge fluence is 5–10 $\mu Cb/cm^2$.

metric study, fuel and oxidizer concentrations were increased at the expense of CO_2 concentration so that $\delta F_2 = -\delta CO_2/2$ and $F_2 = D_2$. The observed increase in CO_2 output energy density is believed to be caused by the increase in energy content of the mixture. Assuming $(F/F_2)_i$ is approximately unchanged for the data of Fig. 4, the observed dependence $J/\ell \sim F_2^{0.8}$ is somewhat weaker than that observed for the case of the DF chain laser. Were the data of Fig. 4 extrapolated to 20% F_2 mixtures, output energy densities of 36 J/ℓ (68 J/ℓ atm) would be predicted.[16,20]

Laser performance data obtained at 200, 400, and 800 Torr are plotted as a function of cavity pressure in Fig. 5. Substituting nitrogen gas for helium gas to buffer the laser mixture is seen to have had little effect on laser performance. Laser output was found to scale nonlinearly with pressure, $J/\ell \sim p^{0.8}$, suggesting that deleterious three-body processes are operative in this chemical laser system. Taken with the data of Figs. 3 and 4, a scaling law for a DF-CO_2 laser of the form $J/\ell \sim (F/F_2)_i^{1/4} F_2^{0.8}$ appears to be valid in the present operating regime. The 800-Torr performance is comparable to that of a DF chain laser using mixtures of comparable chemical energy content and level of initiation. Actual DF-CO_2 performance may, in fact, be somewhat higher than the values reported here. Bulk inclusion damage to the central portion of the ZnSe laser windows was observed to occur after only a few shots at 400 Torr. Laser experiments were precipitously terminated by total fracture of one ZnSe window after the third laser test at 800 Torr.

The predictions of a DF-CO_2 laser model are included in Fig. 5.[21] The initiation level that is required as initial data in the calculations was obtained by matching the model pulse lengths to the experimentally determined pulse lengths. By using this procedure it was found that $(F/F_2)_i = 0.006$ to 0.008 for the data presented herein.

Although the numerical results are not included in the earlier figures, we find that all the trends of the experimental data are correctly predicted by the present code; unfortunately, the model overpredicts the measured energy densities by approximately 50 to 100%, as indicated in Fig. 5. Similar discrepancies have been observed by other investigators who have modeled pulsed

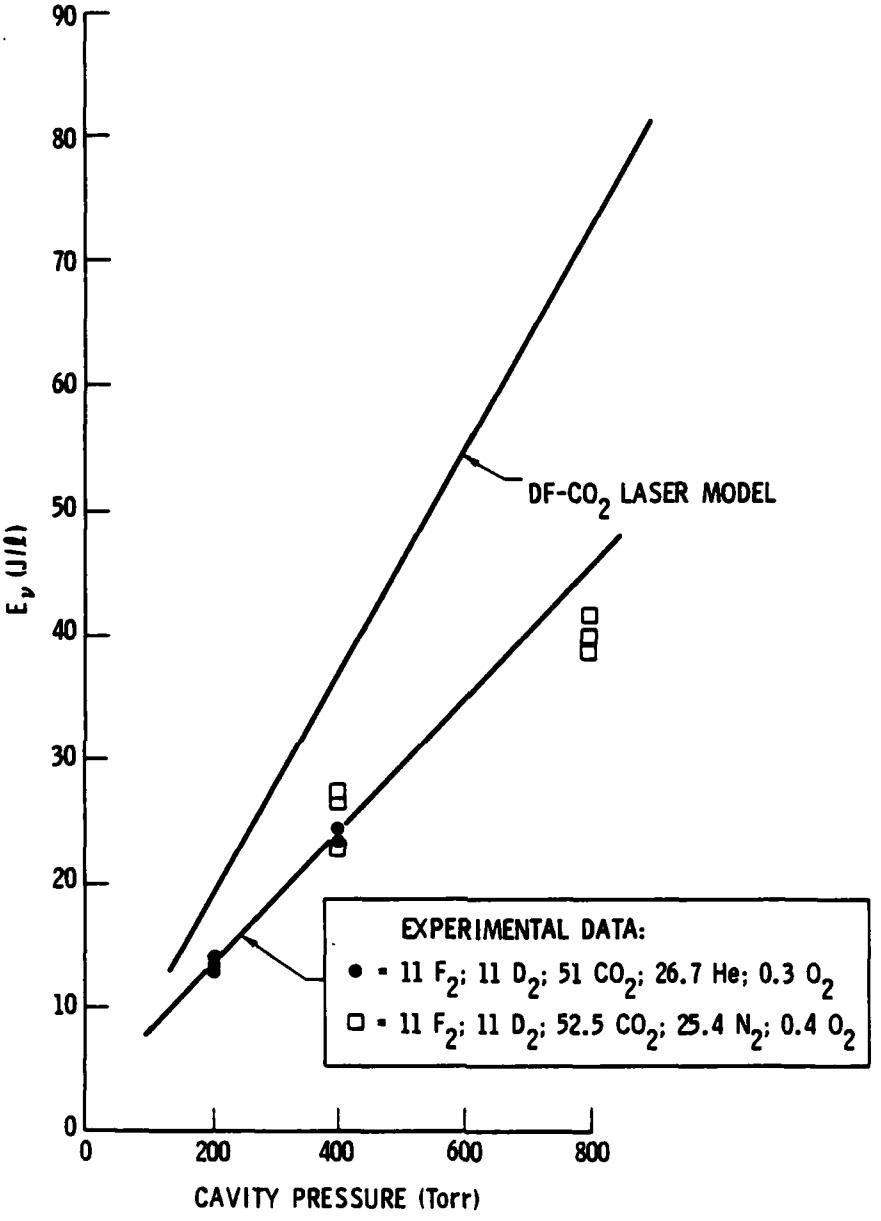

Fig. 5. Pressure Scaling for DF-CO_2 Transfer Laser: Theory and Experiment. Specific energy output from 11 F_2: 11 D_2 mixtures as a function of laser cavity pressure. E-beam charge fluence is 5-10 $\mu Cb/cm^2$.

HF/DF chain-laser performance.[18,22] The cause for this disagreement is unknown at present. We speculate that incorrect values of the assumed chemical-pumping and energy-transfer rates may be responsible for the observed differences.

The largest DF-CO_2 laser output, 82 J (41 J/ℓ), was obtained with an electrical input incident on the extraction volume of about 350 J; chemical efficiency relative to the initial D_2 content was 1.8%. The electrical efficiency for conversion of total incident energy to laser output energy was therefore 23%. Based on the stopping-power data of Ref. 23, the intrinsic electrical efficiency for this case is calculated to be 200%. High overall electrical efficiencies appear possible for the subject laser device when the dimension along the axis of e-beam propagation is made comparable to the range of the electron beam.

IV. CONCLUDING REMARKS

A combined theoretical and experimental study of a DF(HF)-CO_2 transfer laser has been reported. A rotational nonequilibrium DF-CO_2 laser code was developed whose predictions are in good qualitative agreement with experiment. The exploratory data here reported demonstrate that large-volume excitation of DF-CO_2 transfer lasers is feasible and should be compatible with high laser-energy densities and large overall efficiencies. Further improvement in laser-performance is anticipated for mixtures that contain excess F_2 or when the chemical energy content of the laser gas is increased beyond values considered in this investigation. The control of gain spiking and mode beating, by optical injection or other means, is an important area for further research.

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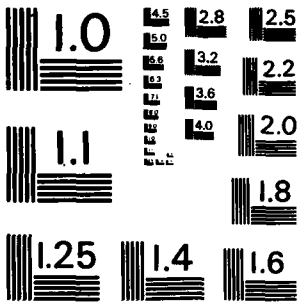

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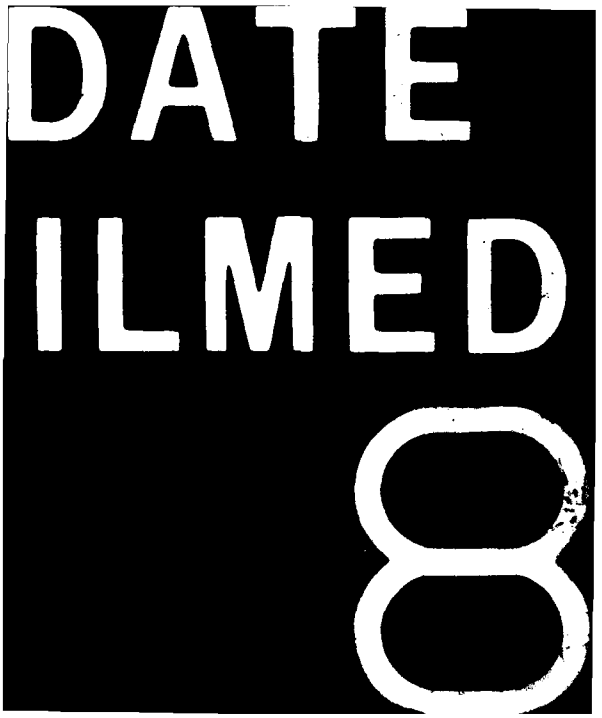
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